

Compact and Low Loss Fan-in/Fan-out Devices with Spatial Optical Coupling for Four-core Fibers

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Abstract— We fabricated spatial optical coupling-based Fan-in/Fan-out devices for four-core fibers with an insertion loss less than 0.28 dB over the C-band. Thermally expanded cores in single-core fibers enable the optical coupling system to be simple compact, and tolerable to assemble.

Keywords— Space Division Multiplexing (SDM), Multi-core fiber (MCF), Fan-in/Fan-out (FI/FO), Thermally expanded-core (TEC) fiber

I. INTRODUCTION

The data traffic in optical communication networks has been increasing exponentially ever since the deployment of dense wavelength division multiplexing systems in the 1990s. However, according to a study of practical single-mode-fiber optical communication systems, capacity limits are coming in the next decade [1]. Under these circumstances, spatial division multiplexing (SDM) technologies using multi-core fibers (MCFs) have been studied as a promising approach to overcome these limits for both submarine networks [2] and terrestrial networks [3]. Installation of a cable including two-core fibers has already been started in the Pacific Ocean as the first implementation of MCF in submarine networks [4]. Fan-in/Fan-out (FI/FO) devices for two-core fibers are being installed in optical repeaters to amplify optical signals by single-core fiber (SCF) amplifiers. Four-core fibers will be used as a further step in the near future and FI/FO devices for them would be also necessary.

Many kinds of FI/FO devices have been reported so far, utilizing such features as fiber bundles [5], 3D-waveguide [6], fused taper fibers [7], and spatial optical coupling with lenses [8-10]. Spatial optical coupling-based devices such as isolators and gain flattening filters have been put to practical use in submarine networks because they have low loss and high reliability. FI/FO devices using micro-lens arrays have been reported [8,9]. They need space to split each collimated beam from different cores to avoid their overlap on the micro-lens array. As a result, the devices are larger in diameter. A spatial optical coupling type FI/FO device without a micro-lens array has also been reported [10]. However, it has the same number of SCF collimators as the number of cores in MCF. As a result, the device also has a large diameter.

In this study, we fabricated compact and low loss FI/FO devices with spatial optical coupling for uncoupled four-core fibers. Thermally expanded-core (TEC) fibers enabled the optical coupling system to be simple and smaller in diameter than previous works of spatial optical coupling FI/FO devices [8-10].

II. OPTICAL DESIGN AND STRUCTURE

A schematic of the optical diagram in Fig. 1(A) shows the FI/FO device we designed and fabricated. It consists of a pair of spherical lenses, an MCF with four cores, and four SCFs. All these lenses and fibers have an AR-coating available for the C-band on their end surfaces. The SCFs have TEC-treated

parts at each end of the fiber. Each of the four cores in the MCF shown in Fig. 1(B) has the same mode field diameter (MFD) of 9.8 μm at λ of 1.55 μm . The MCF has a cladding diameter of 125 μm and the cores are arranged squarely with a nearest core-to-core pitch of 40 μm . Four SCFs are bundled squarely in the square-shaped hole of a ferrule as shown in Fig. 1(C). The SCF core pitch is around 125 μm because they have a cladding of 125 μm in diameter. The SCFs have an MFD of 10.4 μm at λ of 1.55 μm .

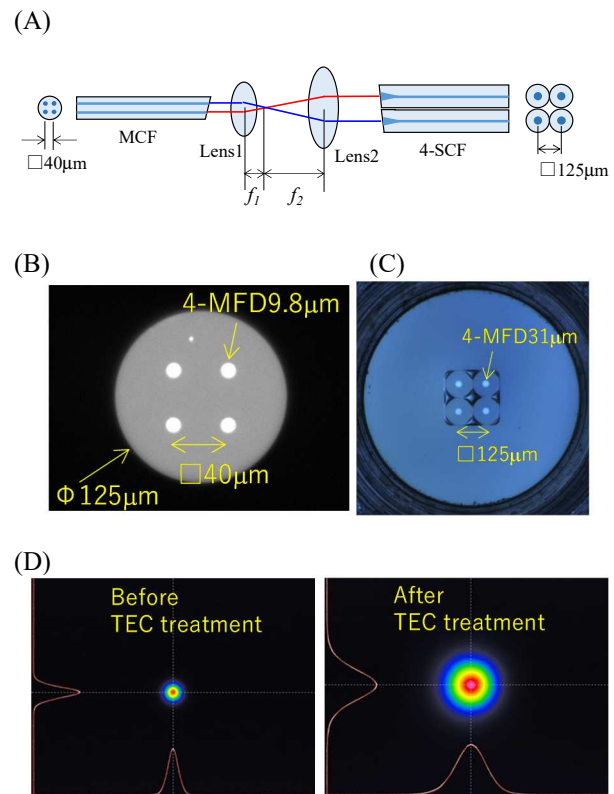


Fig. 1 (A) A schematic of the optical design in the FI/FO device (B) An end-face photo of the MCF used in the FI/FO device (C) An end-face photo of the four-SCF bundle with TEC terminated in a ferrule. (D) A near-field pattern of the SCF before TEC treatment (left side) and that of after TEC treatment (right side)

The TEC parts at the end face of each SCF have a partially larger MFD of 31 μm at λ of 1.55 μm . The MFD of GeO_2 -doped single-mode fibers can be enlarged by heating. Ge in a core is partially diffused into the cladding. Then the distribution profile of Ge changes. As a result, an SCF with a larger MFD can be realized [11]. Measured near field patterns (NFP) before and after TEC treatments are shown in Fig. 1(D). The NFP after the treatment is 3.1 times larger than that before the treatment. No distortion of the mode profile was observed.

As shown in Fig. 1(A), the MCF has an angled end face of 8° to reduce back-reflections. The SCFs also have angled end faces of 2° because the NA of the TEC is around one-third of

the MCF. Lens 1 facing the MCF has a focal length of f_1 , and the other lens, Lens 2 facing the SCFs, has a focal length of f_2 . The magnification of this lens-coupling system is $f_2/f_1 = 3.1\times$. The four cores with a pitch of $40\ \mu\text{m}$ in the MCF can be optically coupled with the four cores with a pitch of $125\ \mu\text{m}$ in the 4-SCF bundle under this magnification. The MFD of the SCFs is 3.1 times larger than that of the MCF, therefore the coupling loss due to MFD mismatch is prevented. In this spatial optical coupling system, the four beams from each core of the MCF go through Lens 1 and are collimated. Then, collimated beams are refocused by Lens 2. The four refocused beams are coupled with the cores of each SCF, and vice versa when the four beams come from each SCF.

The advantage of the use of TEC fibers is not only the prevention of MFD mismatch but also a large tolerance in X, Y, and Z misalignments. An SCF bundle is aligned and fixed with a sub-assembly which consists of an MCF and two lenses as shown in Fig.2 (A). Loss change curves in X and Z axes are shown in Figs. 2(B) and (C). These can be calculated by Marcuse's formula [12]. An SCF with an MFD of $31\ \mu\text{m}$ is insensitive to misalignment.

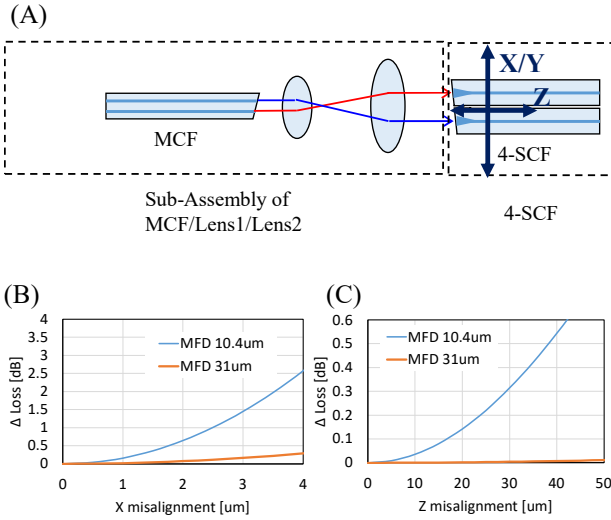


Fig. 2 (A) A schematic diagram of misalignment between a sub-assembly of MCF/Lens1,2 and a 4-SCF (B) Relationship of 4-SCF X-axis misalignment to loss increase in calculation (C) Relationship of 4-SCF Z-axis misalignment to loss increase in calculation

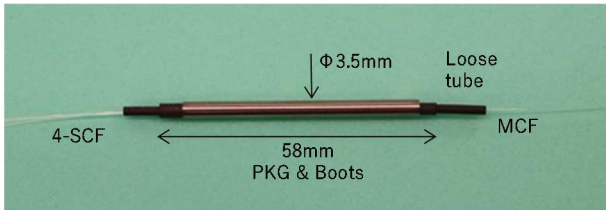


Fig. 3 A photo of the fabricated FI/FO device housed in a SUS tube 3.5 mm in diameter

III. FABRICATION

Firstly, an MCF collimator was sub-assembled. Secondly, the sub-assembled MCF collimator, Lens 2, and a 4-SCF bundle were simultaneously aligned with the optical powers of all four lanes monitored. Thirdly, the MCF collimator and Lens 2 were welded together by a laser. Finally, the 4-SCF bundle was welded with Lens 2, after a compensation alignment between Lens 2 and the 4-SCF bundle. The assembled FI/FO device was housed in a metal tube as shown

in the photograph in Fig. 3. The size of it was 3.5 mm in diameter and 58 mm in length including boots on both sides.

IV. OPTICAL CHARACTERISTICS

We fabricated two devices for a FI/FO device pair. The IL and the polarization-dependent loss (PDL) spectrums of each device were measured over the C-band.

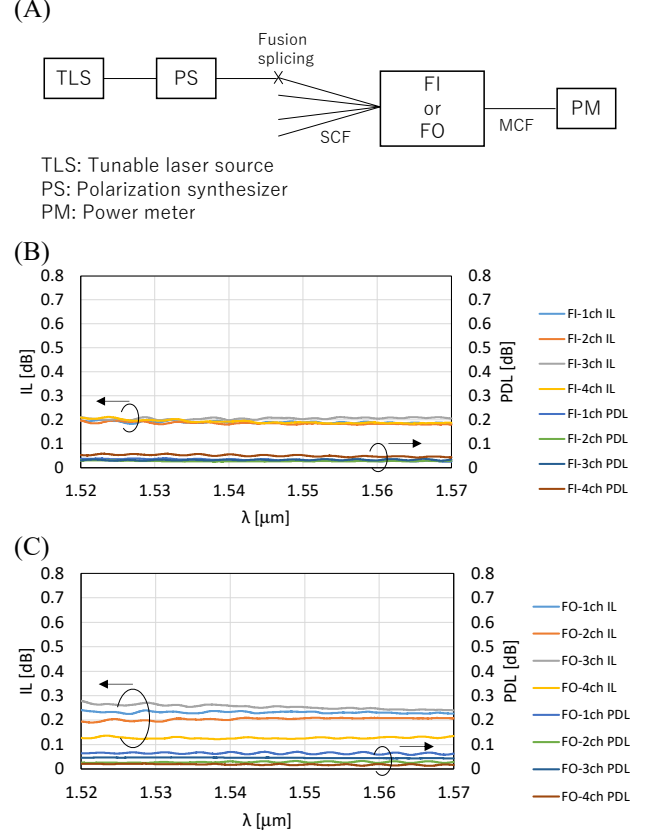


Fig. 4 (A) The measurement setup for the IL and PDL spectrums at C-band (B) The measured IL and PDL spectrums of the fabricated FI device (C) The measured IL and PDL spectrums of the fabricated FO device

The measurement setup was as shown in Fig. 4(A). A C-band tunable laser source was used to measure the wavelength dependency. The measured IL and the PDL spectrums of the FI device and FO device are shown in Fig. 4(B) and (C), respectively. The IL of FI and FO were less than 0.22 dB and 0.28 dB, respectively throughout the C-band. The average IL of all 8 lanes in the FI/FO devices was 0.20 dB. The IL calculated by a Zemax optical tool with the optical model having no misalignment was 0.1 dB. The main additional loss factor was presumed to be due to the SCF's misaligned arrangement in the 4-SCF bundle. When the FI/FO devices were aligned with each lane individually monitored, each monitored lane showed an IL less than 0.15 dB. Another factor may be the internal loss of TEC fibers. The wavelength-dependent losses throughout the C-band were less than 0.04 dB. The PDLs throughout the C-band were less than 0.07 dB. The average PDL of all 8 lanes in C-band was 0.04 dB. The crosstalk (XT) and the isolation (ISO) were measured at λ of $1.55\ \mu\text{m}$. The measurement setup was as shown in Fig. 5 (A). MCFs of the FI and FO devices were spliced into each other. The XT was defined as a light power ratio leaked to other output ports of the FO. It is expressed as a minus sign. The ISO was defined as a light power ratio leaked to other input

ports of the FI. It is expressed as a plus sign. The light was input from one port of the FI, and then output powers from the other seven ports were measured. The light was input from FI-port1,2,3,4, in turn. The measured XT and ISO are shown in Figs. 5(B) and (C). All XT were less than -57 dB and all ISO were more than 63 dB.

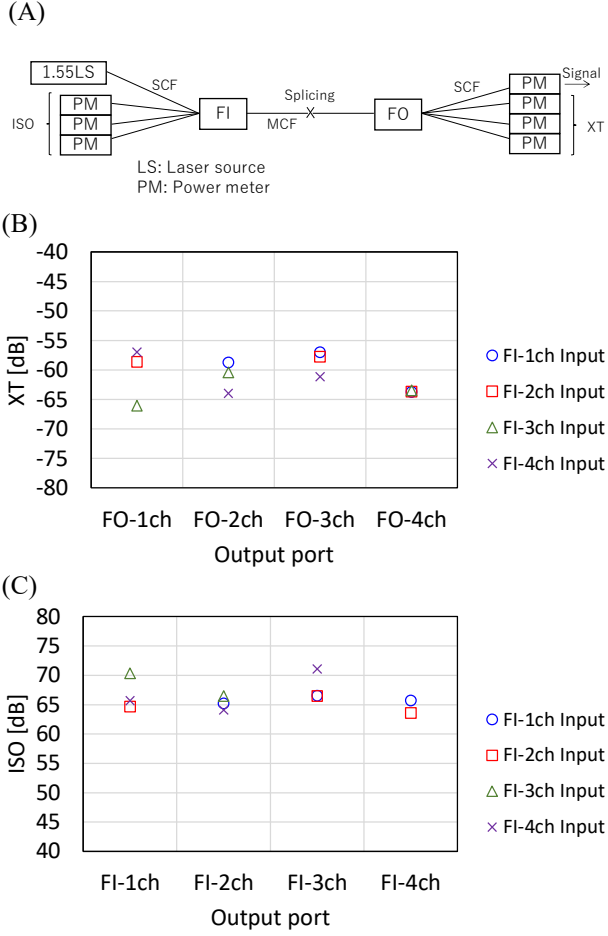


Fig. 5 (A) The measurement setup for the XT and ISO in FI/FO devices pair at λ of 1.55 μm (B) The measured XT (C) The measured ISO

The return loss (RL) at λ of 1.55 μm in the FI/FO devices is shown in Fig. 6. It was measured by the optical-continuous-wave-reflectometry (OCWR) method. All lanes had RL more than 53 dB.

The measured temperature-dependent loss in the FO device is shown in Fig. 7. The environmental temperature was cycled over the -10 to 70°C range. The loss change over the temperature range in six cycles was less than 0.06 dB in all four lanes.

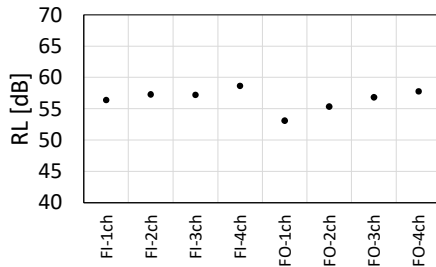


Fig. 6 The measured return loss at λ of 1.55 μm of the FI/FO

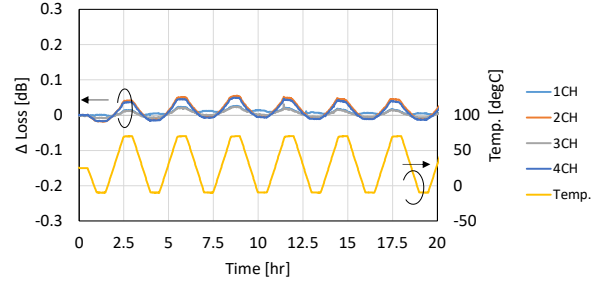


Fig. 7 The measured thermal dependent loss at λ of 1.55 μm over the temperature range of -10 to 70°C in the FO device

V. CONCLUSION

We have designed and fabricated FI/FO devices for uncoupled four-core fibers. TEC fibers with an MFD of 31 μm enabled the optical design to be simpler than those in previous works. The device has only two spherical lenses thanks to the TEC fibers. The measured IL was less than 0.28 dB throughout the C-band. The measured XT was less than -57 dB, and the measured ISO was more than 63 dB at λ of 1.55 μm . The size of the device was 3.5 mm in diameter and 58 mm in length. This compact and low loss FI/FO device could be useful in developing submarine SDM network systems.

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